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The role of the predicted present in artificial and natural cognitive systems

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Abstract. In previous work, we have argued that a sophisticated cognitive system with a complex body must possess configurable models of itself (or at least its body) and the world, along with the necessary infrastructure to use the modelled interactions between these two components to select relatively advantageous actions. These models may be used to generate representations of the future (imagination) and the past (episodic memory). In this paper we will explore some problems surrounding the representation of the present arising from the use of such models in the artificial cognitive system under development within the ECCEROBOT project. There are two aspects to consider: the representation of the state of the robot's body within the self model, and the representation of the state of the external world within the world model. In both natural and robotic systems, the processing of the sensory data carrying state information takes a considerable time, and so any estimates of the present states of both the agent and the world would have to be obtained by using predictive models. However, it appears that there is no need for any such representations to be generated in the course of selecting a course of action using self and world models, since representations are only of the future or the past. This may call into question the utility and timing of the apparent perception of the present in humans.

Keywords. Prediction, Robotics.

1. Introduction

In previous work, we have argued from first principles that a sophisticated cognitive system with a complex body must possess configurable models of itself (or at least its body) and of the world, along with the necessary infrastructure to use the modelled interactions between these two components to select relatively advantageous actions. We have reviewed the biological and psychological evidence supporting the view that humans possess and use such an architecture, and we have successfully demonstrated such a scheme – essentially a kind of imagination, which we call functional embodied imagination – on a complex robot [1,2]. We have since taken note of the recently established connections between imagination and episodic memory in humans in order to consider the possible extension of our scheme to providing a kind of episodic memory for the system's actions [3].

As noted in [4], many authors have pointed out that the possession and use of a self-model may ultimately lead to consciousness, or at least to many of the cognitive features that seem to be associated with consciousness. There are many pitfalls in

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attempting to deal directly with the notion of consciousness in artefacts, but these can be avoided by adopting the representational principle of experience proposed in [3]. This makes the very simple assumption that whatever is (consciously) experienced in a system must be represented, but that mere representation does not necessarily imply experience. By analysing cognitive architectures for what needs to be represented for purely functional reasons, this places a useful constraint on what might be experienced within such systems. In our own architecture, we have so far dealt with what we call functional embodied imagination and (to some extent) episodic memory. Although imagination in general deals with counterfactuals, functional embodied imagination – a way of deciding what to do next – is about the future; in contrast, episodic memory is always about the past. For completeness, in this paper we will explore the issues surrounding the representation of the present, and we will use the version of our architecture under development within the ECCEROBOT project [5].

But what kinds of issues might arise in the representation of the present? There are many possibilities, and we will consider only a small subset here. We will be concerned only with the representation within the system at a time T of the state of the robot and the external world at time T. We will not be concerned with the representation of time itself within the system, which may not be intrinsically temporal, nor with anything corresponding to the subjective experience of time. Instead, our focus will be on the function and nature of the state representation. Its function, defined very narrowly, will be assessed in relation to its contribution to the selection of relatively beneficial actions through the mechanism of internal simulation. The nature of the representation is constrained by the unavoidable existence of delays in both sensing and sensory processing: if any representation of the present exists, it must necessarily be a representation of the *predicted present* based on data from the past. This was first articulated in the context of visual perception by Helmholtz [6], who measured the surprisingly low speed of neural conduction, and who then invoked 'unconscious inference' as the mediating process in producing a timely perception, a position developed much further and much later by Richard Gregory. (Our use of the phrase 'predicted present' is partly to differentiate it from Edelman's 'remembered present'[7], which applies to subjective experience; nevertheless, both use data from the past.)

2. ECCEROBOT: Body, sensors, actuators, control, and cognition

The European project ECCEROBOT (Embodied Cognition in a Compliantly Engineered Robot) [5] is exploring the possible connections between a specifically human embodiment, and specifically human cognitive characteristics. It centres around a series of robots each of which copies the musculoskeletal structure of the human body, with a human-like skeletal torso, and analogues of muscles elastically coupled to the bones via elastic tendons. Figure1(a) shows a recent example, the ECCEROBOT Design Study (EDS). This anthropomimetic approach [8] contrasts with that of conventional humanoid robots, which, although they fit within a roughly human envelope, are constructed using the same technology as industrial robots, with stiff, precisely controlled motors and joints. There are four key characteristics which distinguish anthropomimetic robots like ECCEROBOT from traditional humanoids: tendon-driven redundant actuation, multi-articular joint actuators, compliance, and complex joints (see [9] for details). While these succeed in producing a distinctively human (or animal) embodiment, they also make it almost impossible to use the standard engineering control techniques which conventional humanoids are so carefully designed to facilitate. It is for this reason that a key part of the ECCEROBOT project is to investigate how such robots might be controlled – and of course, the control methodology will necessarily both constrain and enable the possibilities for cognition.

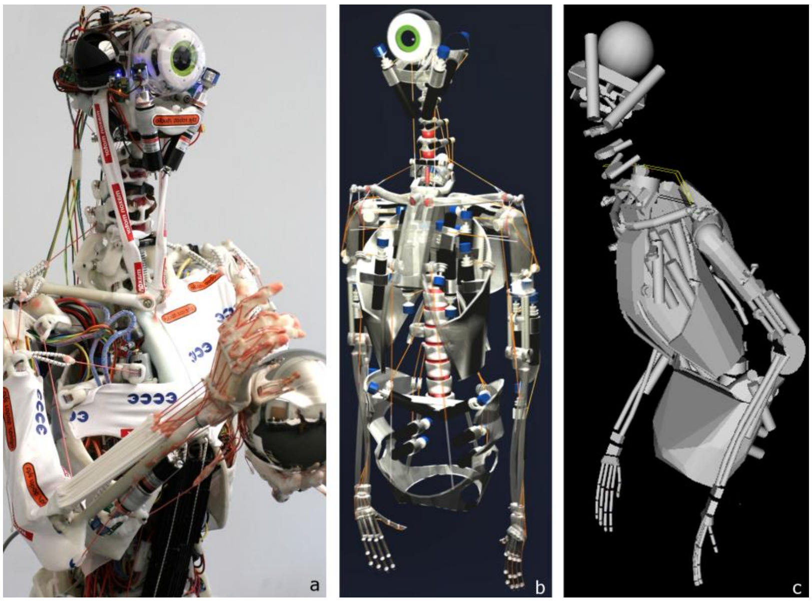

Figure 1. (a) An anthropomimetic robot, the ECCEROBOT Design Study (EDS). (b) 3D Static structure captured in Blender model. (c) Dynamic behaviour modelled in the Bullet physics engine.

In an ideal world, the controller of choice would be a biologically inspired neural system. However, it is still the case that not enough is known about the mechanisms of muscular control to make this a practicable proposition for such a complex robot, with its 44 motors, 70 jointed components, and almost 100 degrees of freedom. (Note that the robot is underactuated, with many degrees of freedom under passive control.) Instead, we are investigating three different but possibly complementary methods: classical engineering control, sensory-motor strategies, and functional embodied imagination. We have made some progress with the first [10], but its limitations have now become clear. Work on the second, which will combine the principles of embodiment and self-organisation set out in [11] with sophisticated information based metrics to characterise sensory-motor interactions, is just beginning. The rest of this paper deals with the implementation of functional imagination and its likely cognitive consequences.

In order to act appropriately, the control system needs information about the robot's state, the state of the environment, and the relation between the robot and the environment. Ideally, all of this information would be derived from sensors mounted on the robot, and those sensors and their associated processing architectures would be biologically inspired. We have satisfied the first requirement – there are no offboard sensors – but the severe constraints of the physical embodiment, as well as our substantial ignorance about how the nervous system processes sensory information, have led us to adopt a more pragmatic approach to the second.

The key provider of information about the environment is vision. After initial investigations using a single camera (hence the single eye of the EDS), which is known to be capable of providing all the required information [12], we have adopted the Microsoft Kinect [13] as the main visual sensor. The Kinect provides a depth map co-registered with an RGB image; these data are processed using GPU accelerated techniques to produce a simplified texture mapped depth map in from tens to hundreds of milliseconds [14]. Within this map, known objects can be recognised and localised, and can then be replaced with detailed precompiled physically and cosmetically correct models as described below. The position of the robot's head in relation to the environment is known from the Kinect data; the static and dynamic configuration of the rest of the body is derived from a knowledge of the positions of the motors, the lengths of the muscle/tendon units, the motor currents, and the tensions in the tendons. All sensory and motor data are managed by a distributed control architecture [15].

3. Delays, and how to deal with them

3.1. Motor Planning

The motor planning strategy for ECCEROBOT's compliant, complex and non-linear structure takes as its premise the assumption that, in our present state of knowledge, it is unlikely that either an adequate analytical model or a suitable control signal could be designed. We have therefore taken the approach of using a generic physics engine to build a detailed simulation model of the robot's structure and joints, including models of the passively compliant tendons, the motors and gearboxes. By stepping the physics model forward in time under the influence of simulated motor inputs we can then use it as a forward model supporting search or learning strategies in kinodynamic space to attempt to obtain a sequence of open loop motor inputs taking the model from a given starting state (the captured state of the robot and environment) to a target state (e.g. grasping an object). This sequence would then be downloaded to the real robot for execution.

3.2. Delay Compensating Control Architecture for ECCEROBOT

As with any control system, delays must be taken into account. The most important delay is the end to end delay between the state of the system at a given time, and the earliest time that a control output based on the sensing of that state can begin to act. The total end to end delay is therefore $d_{in} + d_{out}$ where d_{in} is the time to capture, transmit and process sensor readings to obtain the relevant state estimate, and d_{out} is the time taken to generate a new (or revised) motor activation plan plus the time to transmit this to the physical motors. Thus, if $S(t)$ is the robot state at time t, then the motor planner must be initialized with the state $S(t + d_{in} + d_{out})$ as this is the earliest state of the system where any new motor plan can have any physical effect on its motion. Of course, during d_{in} and d_{out} the robot will continue to be moved under the existing motor plan, and so d_{in} must include not only the time for computing $S(t)$ from the sensor data but also the time $d_{predict}$ for rolling this state estimate forward to $S(t + d_{in} + d_{out})$. The output side of the delay-compensation control architecture is summarized in the schematic Figure 2, in which for convenience $(d_{in} + d_{out})$ is written as d.

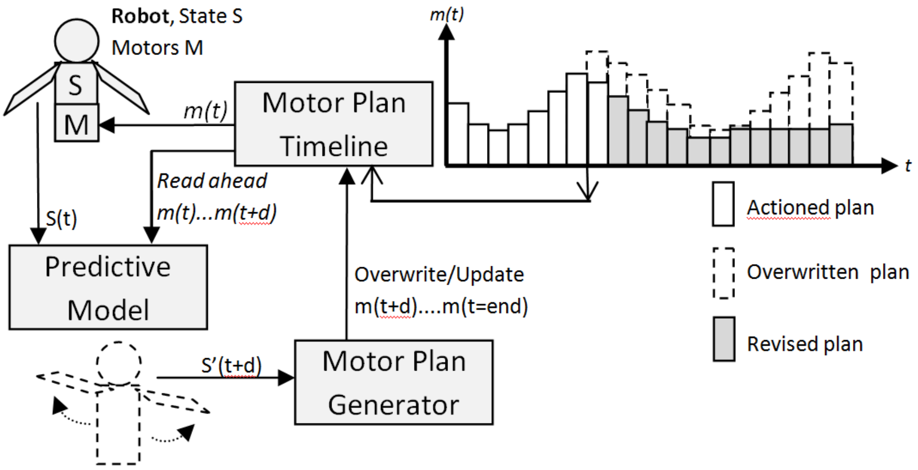

Figure 2. Output delay compensation control architecture for ECCEROBOT.

The current proposed motor plan to reach the goal state is quantized and queued into the motor timeline cache. Control signals are sent to the robot motors continuously, read from this single master queue. The model of the robot and its elastic actuators takes the estimated current state *S* and drives it with the current motor plan, obtained by reading out the set of upcoming signal sequences covering the period *d* from the timeline cache. A predicted future state *S(t+d)* can thus be obtained. The motor planner now locates a new best plan that will take the robot from *S(t+d)* to the goal state. Revised plans are loaded into the queue, overwriting the old values but starting from the time step at $t + d$.

3.3. Modelling an ECCEROBOT

To create a sufficiently fast non-linear, dynamic model we chose to use the Bullet physics engine [16] which was originally designed for fast 3D games. It is nevertheless a modern, customizable and open-source update on older engines such as ODE, with GPU accelerated collision detection and constraint solving planned for release shortly. Custom extensions have been added to Bullet to model the behaviour of the elastic muscles, pulleys, gearboxes and motors.

A first-pass model, shown in Figure 1(b), was produced using the Blender tool to create a static 3D model of the robot from extensive measurements, photographs and videos. This was exported in sections to Bullet, where joint constraints were then added to create a dynamic model, as shown in Figure 1(c). Finally motor attachment points and pulleys – or pulley-like behaviour where muscle cables wrap around the shoulder or scapula – were added.

To tune the first-pass model's dimensions and parameters to match the robot sufficiently well is a challenging task, but promising early work uses genetic algorithms to search for the best parameter combinations by selecting for the closest match between real and simulated proprioceptive signals.

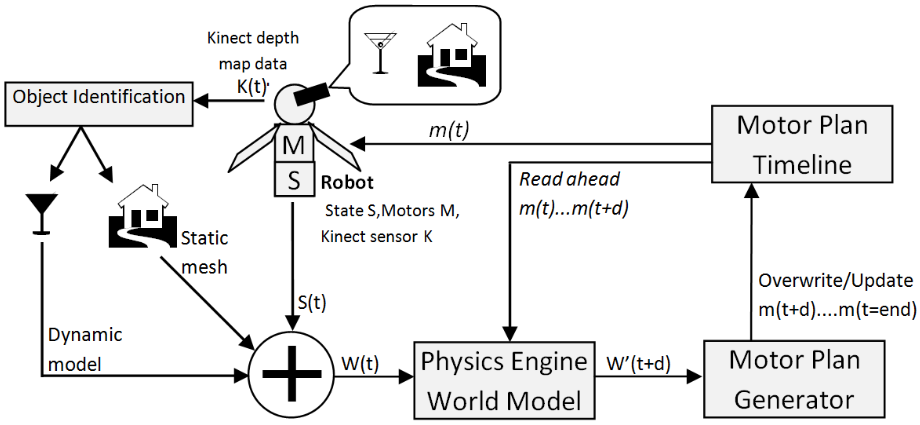

Figure 3. Control architecture using the physics engine to merge environment capture with the robot model

3.4. Merging the robot and environment to create a simulated 'inner world'

Planning tasks where the robot must move about and interact with objects cannot take place without the robot model being situated accurately within the model of the environment, and in relation to the modeled target object. A significant attraction of a generic physics engine approach is that the simulation can be extended to incorporate not just the robot but also a three dimensional model of the environment and the target object. Furthermore, using the Kinect sensor and object recognition [14], these models can be added selectively as either homogeneous static 'collision shapes' (the environment, typically a room) or as full dynamic models in their own right – for example, a target object such as a bottle that is to be grasped and lifted. Once this is achieved this now unified physics-based world model can be used to plan and select the best set of activation signals. Figure 3 shows a schematic of this process. The world state W(t) is generated by merging the state of the robot model with a static collision mesh along with explicit dynamic models of recognized potential target objects. W(t) is then stepped forward in the physics engine for a period $(d_{in} + d_{out})$ before motor planning is commenced.

4. The predicted present

A range of studies in both cognitive science and neuroscience directly support the notion that the state perceived when planning or executing a motor task may not correspond to the state captured at the moment of sensory input but rather to an estimate of a predicted future state. The flash-lag effect [17], where a moving dot is perceived to be ahead of a static one, is a well known simple example, although there are competing interpretations. Similarly, the auditory continuity [18] and phonemic restoration [19] illusions, where interruptions in sensory data are not perceived at all by a subject so long as the data resumes along a predictable path, demonstrate how some conscious perceptions appear to derive not from direct data but from a predicted state generated some time after a period of data acquisition.

More interesting still, Ariff et al. [20] found that the position of eye saccades tracking an unseen reaching movement appeared to reflect the output of a state predictor, rather than the actual position. The saccades correctly predicted the hidden hand position until the hand was subjected to a force field, when the eyes at first continued to track the predicted path until the saccades were briefly inhibited and a corrected estimated position was tracked. Similarly, Fourneret and Jeannerod [21] found that subjects performing a motor movement were actually more conscious of the relevant stage in their planned movement than in their actual movement, which they had been induced to unconsciously distort.

While this type of evidence emphasizes that what appears to be consciousness of state is in fact consciousness of predicted state, there is little satisfactory evidence concerning the objective timing of the awareness of the state and the state itself, which should be simultaneous to qualify both as dealing with 'the present'. Conscious perception contains many temporal anomalies for which resolution is often sought in the idea of retrospectively 'backdating' experience to yield a coherent account of events, as for example in the cutaneous rabbit illusion [22], where a series of taps on the arm appear (wrongly) to the subject to have followed a smooth extrapolated path. The best that can be said at the moment is that the apparent, or subjective, present is in many cases demonstrably the outcome of a prediction from previous data.

As noted in Section 1, any representation of the present in an artificial system must be a representation of a predicted present; this must also be true of any representation of the present in a natural system. Of course, given sufficient computational resources, it is certainly possible for a cognitive system, whether artificial or natural, to construct a representation of a predicted present, as is routinely done in certain engineering systems. However, in our cognitive system there is no *requirement* for any explicit representation of the present; instead, the system contains only data-driven representations of the recent past and predicted representations of the near future. If the human cognitive system is of the same basic type as that under development for ECCEROBOT, in which no representation of the present is required, then the application of the representational principle of experience raises the intriguing possibility that our own conscious perception, which subjectively appears to be of the present, must in fact be either of the near future or the recent past. This hypothesis has the potential to account for the existence of at least some of the anomalies mentioned above; even if it cannot account for particular anomalies without considerable further work, further theoretical and experimental investigation would seem to be worthwhile.

5. Conclusions

In both natural and artificial systems, sensory and computational constraints mean that any representation of the present must necessarily be a prediction from data gathered in the past. In an artificial embodied cognitive system which uses a form of imagination to discover and select a beneficial sequence of motor activations, the most important representation is of the predicted state of affairs in the near future, and there is no need for any representation of the present. Evidence from psychology and neuroscience indicates that many apparent perceptions of the present are clearly derived from predictions based on past data, but it is not clear whether the predictions refer to states in the recent past, the actual present, or the near future. Biologically inspired cognitive architectures, especially those dealing with embodied systems in dynamic environments, should therefore consider the issue of the representation of the present, particularly when dealing with analogues of consciously mediated perception, and should take note of the possibility that a representation of the predicted present, while technically possible, may be neither necessary nor appropriate.

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References

[1] Marques, H.G. and Holland, O. [2009] Architectures for functional imagination. *Neurocomputing* 72, 743-759

[2] Marques, H.G. [2010] Functional Embodied Imagination. Ph.D. thesis, University of Essex.

[3] O. Holland and H.G. Marques (2010) Functional embodied imagination and episodic memory. *International Journal of Machine Consciousness* Special Issue on Biologically Inspired Cognitive Architectures 2:2 pp 245-259

[4] O. Holland and R. Goodman (2003) Robots with internal models: a route to machine consciousness? *Journal of Consciousness Studies*, Special Issue on Machine Consciousness, vol 10, No 4, 2003

[5] eccerobot.org

[6] Helmholtz, H. von (1909/1925) *Physiological optics, vol. 3,* trans. J. P. C. Southall. Optical Society of America.

[7] Edelman, G. M. (1989) *The Remembered Present: A Biological Theory of Consciousness* (Basic Books, New York).

[8] O. Holland and R. Knight (2006) The anthropomimetic principle. *AISB Symposium on Biologically Inspired Robots*, Bristol.

[9] H.G. Marques, M. Jäntsch, S. Wittmeier, C. Alessandro, O. Holland, C. Alessandro, A. Diamond, M. Lungarella, and R. Knight (2010). ECCE1: the first of a series of anthropomimetic musculoskeletal upper torsos. In *Proceedings of 10th International IEEE/RAS Conference on Humanoid robotics (Humanoids2010)*

[10] V. Potkonjak, B. Svetozarevic, K. Jovanovic, O. Holland (2010) Biologically-inspired control of a compliant anthropomimetic robot, The 15th IASTED International Conference on Robotics and Applications, Cambridge, Massachusetts, pp 182-189

[11] Pfeifer, R., Lungarella, M., Iida, F. (2007). Self-organization, embodiment, and biologically inspired robotics, *Science*, Vol. 318, 1088-1093

[12] Richard A. Newcombe and Andrew J. Davison (2010) Live Dense Reconstruction with a Single Moving Camera, Computer Vision and Pattern Recognition (CVPR2010)

[13] http://www.xbox.com/en-GB/kinect

[14] D. Devereux, B. Mitra, O. Holland & A. Diamond, Using the Microsoft Kinect to model the environment of an anthropomimetic robot. Submitted to the Second IASTED International Conference on Robotics (ROBO 2011)

[15] M. Jäntsch, S. Wittmeier & A. Knoll (2010) Distributed control for an anthropomimetic robot. *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems,* IROS 2010, pp. 5466-71

[16] Bullet Physics. Accessed: 25.5.2011. [Online]. Available at http://bulletphysics.org, 2011.

[17] R. Nijhawan (1994) Motion extrapolation in catching. *Nature*. 370, 256-7

[18] S. Grossberg (1995) The Attentive Brain. *American Scientist*, 83, 438-449

[19] S. Grossberg & C.W. Myers (2000) The resonant dynamics of speech perception: interword integration and duration-dependent backward effects. *Psychological Review*, 107(4), 735-767

[20] G. Ariff et al. (2002) A real-time state predictor in motor control: study of saccadic eye movements during unseen reaching movements. *Journal of Neuroscience*, 22(17), 7721-7729

[21] P. Fourneret & M. Jeannerod (1998) Limited conscious monitoring of motor performance in normal subjects. *Neuropsychologia*, 36(11), 1133-1140

[22] M. P. Kilgard & M. Merzenich (1995) Anticipated stimuli across skin. *Nature*, 373. 663